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Report No. 32

Petrography of Metamorphic Rocks from the Miller Range, Antarctica

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ABSTRACT

Rock samples collected from the metamorphic rocks of the Nimrod Group in the Miller Range, Antarctica, comprise six lithological groups: mica schists, metaquartzites, banded gneisses, augen gneisses, marbles and amphibolites. Mineral parageneses indicate that these rocks have been regionally metamorphosed to the lower almandine-amphibolite facies of the Barrovian facies series. Chemical analyses calculated from petrographic modes of 13 representative thin sections indicate that the amphibolites were derived from basaltic rocks, but that the principal sources for the remaining five lithologies were sedimentary.

ACKNOWLEDGMENTS

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INTRODUCTION

The Miller Range is located in the central Transantarctic Mountains at about 83°S, 157°W (Figs. 1 and 2). The range trends north-south and is about 80 km long and 30 km wide at its maximum. It is an isolated area of bedrock at the edge of the Polar Plateau, separated from the adjacent ranges of the Transantarctic Mountains by the Nimrod Glacier and its tributary, the Marsh Glacier. The nearest outcrops to the Miller Range are about 20 km away, across these two glaciers. The Miller Range is divided into a number of massifs, separated by small tributaries of the Marsh Glacier. The highest points show evidence of glaciation. The present maximum supra-glacial relief is about 1700 m.

The geology of the area has been described by Gunn and Walcott (1962), Grindley, McGregor and Walcott (1964), and Grindley (1967). The range was first visited in 1957-58 by a New Zealand survey party of the Commonwealth Trans-Antarctic Expedition. In 1959-60 a New Zealand group visited the southern extremity, the geology of which is described briefly in Gunn and Walcott (1962). In 1961-62 a third New Zealand expedition did more detailed survey and geological work, which is described by Grindley, McGregor and Walcott (1964), and Grindley (1967). Geochronological work on rocks from the Miller Range was published by McDougall and Grindley (1965).

During November and December 1967 the writer, as a member of the Beardmore Glacier geological party from the Institute of Polar Studies of The Ohio State University, studied the geology of the Miller Range south of the Argosy Glacier. A preliminary report on the field work by this group has been published by Barrett _et al_. (1968). A geological map which covers the Miller Range and part of the Queen Elizabeth Range at a scale of 1:250,000 (Barrett _et al_., in press) will be published shortly.

GENERAL GEOLOGY

The geology of the Beardmore-Nimrod Glacier area is summarized in Table 1. A basement complex of igneous, metamorphic and sedimentary rocks is overlain with pronounced unconformity by a thick sequence of sedimentary rocks, predominantly continental in origin and Devonian to Triassic in age (the Beacon strata of some authors). The Beacon rocks are intruded by sills and dikes of tholeiitic diabase, dated by the K-Ar method at between 147 and 190 m.y. (Webb and Warren, 1965). Basaltic volcanic rocks, which overlie the Beacon rocks in the Beardmore Glacier area, give K-Ar dates between 163 and 179 m.y. (D. H. Elliot, personal communication).

Four groups of rocks have been distinguished in the basement complex of the Beardmore-Nimrod Glacier area. The high-grade regionally metamorphosed rocks of the Nimrod Group are confined to the Miller and

Fig. 2 - Miller Range: aerial view from the north. Corner Nunatak in foreground. Marsh Glacier at left. Polar Plateau in the distance, center and right.

Table 1 - Stratigraphy in the Beardmore-Nimrod Glacier area

Group or Sequence	Age	Formation	Description	Thickness (m)
Ferrar Group	Jurassic	Kirkpatrick Basalt Ferrar Dolerite Prebble Fm.*	Tholeiitic flows, rare shale lenses with conchostracans, ostracods. Numerous sills and a few dikes. Volcanic mudflows, agglomerate, tuff and tuffaceous sandstone.	600 about 1000 0-500
Beacon Sequence	Triassic	Falla Fm. Fremouw Fm.	Sandstone, shale, Dicroidium; tuff dominates upper part. Sandstone, greenish-gray mudstone: logs, coal, Dicroidium near top.	160-530 620
			Disconformity	
	Permian	Buckley Fm. Fairchild Fm. Mackellar Fm. Pagoda Fm.	Lithic sandstone, dark-gray shale, coal, Glossopteris. Massive arkosic sandstone. Dark shale and fine sandstone. Tillite, sandstone, shale.	about 750 160 90 100-400
			Disconformity	
	Devonian(?)	Alexandra Fm.	Orthoquartzite, sandstone.	about 400
			Angular Unconformity	
	Ordovician(?)	Hope Granite	Porphyritic microcline-biotite-granite, granodiorite, quartz-diorite, pegmatite, lamprophyre.	
Byrd Group	Lower to Middle Cambrian	Shackleton Limestone	Limestone (in places with archeocyathids), shale, conglomerate.	> 8000
Beardmore Group	Uppermost Precambrian	Goldie Fm.	Graywacke, phyllite, quartzite, marble, schist, hornfels.	> 7000
Nimrod Group	Precambrian		High-grade pelitic, quartzo-feldspathic and calcareous meta-sediments, marbles, and amphibolites.	?

*Possibly Triassic

Geologists Ranges. To the east and north low-grade metasediments of geosynclinal aspect, the Goldie Formation, are overlain by the Shackleton Limestone, which locally contains Cambrian archeocyathids. All these rocks were folded and intruded by granite plutons in pre-Devonian time. These granites have been correlated with the Hope Granite of the lower Beardmore Glacier. In the Miller Range granites have given K-Ar dates between 445 and 478 m.y. (McDougall and Grindley, 1965).

Unlike the adjacent ranges, the Miller Range is composed entirely of the basement complex: regional metamorphic rocks of the Nimrod Group, intruded by stocks of Hope Granite. The Nimrod Group, with which this paper is concerned, consists principally of mica schists, banded gneisses, augen gneisses, metaquartzites, marbles and amphibolites.

Grindley, McGregor and Walcott (1964) subdivided the rocks into four successive formations, but this distinction is not followed by the writer. The rocks represent the pelitic, quartzo-feldspathic, calcareous, and basic chemical classes of metamorphic rocks. The principal parent rocks were probably pelitic and quartz-feldspathic sediments with some carbonates. Considerable quantities of amphibolite in some areas, notably Gerard Bluffs, indicate the influence of basic igneous activity.

In the Miller Range the Hope Granite is a variably porphyritic medium- to coarse-grained microcline-biotite-granite. It forms steep-sided stocks with chilled margins, which intrude the Nimrod Group with marked discordance. Locally, mobilization of country rock has occurred (Fig. 3). Numerous pegmatite and aplite dikes and sills occur near the granite margins. The Hope Granite crops out in three areas of the Miller Range. Two stocks, each at least 20 km across, are centered in the Skua Glacier and Martin Dome areas. A third, much smaller, outcrop occurs at Orr Peak, and is partially roofed by gneisses and schists (Fig. 4). The petrography of these granites has not yet been described. However, the megascopic lithological similarities of the three outcrops suggest that they may be connected at depth. Hope Granite also occurs at Moody Nunatak, which is 20 km east of the junction of the Argosy and Marsh Glaciers and the nearest outcrop in that direction. The outcrops at Moody Nunatak, Orr Peak and Kreiling Mesa may be part of the same body of granite. In this case a large part of the Marsh Glacier at this latitude may be floored by granite.

STRUCTURE AND METAMORPHISM

The structure of the Nimrod Group has been described by Grindley, McGregor and Walcott (1964, p. 210). The rocks have been strongly folded about subhorizontal axes striking approximately northwest. Foliation in the schists and gneisses dips regionally to the southwest, mostly at shallow to moderate angles. Locally there is considerable variation in strike and dip, especially near granite margins. Megascopic

Fig. 3 - Banded gneisses invaded by porphyritic granite; Dike Cirque. The felsic portions of the gneisses have been mobilized, while the mafic bands have broken up and the fragments disoriented.

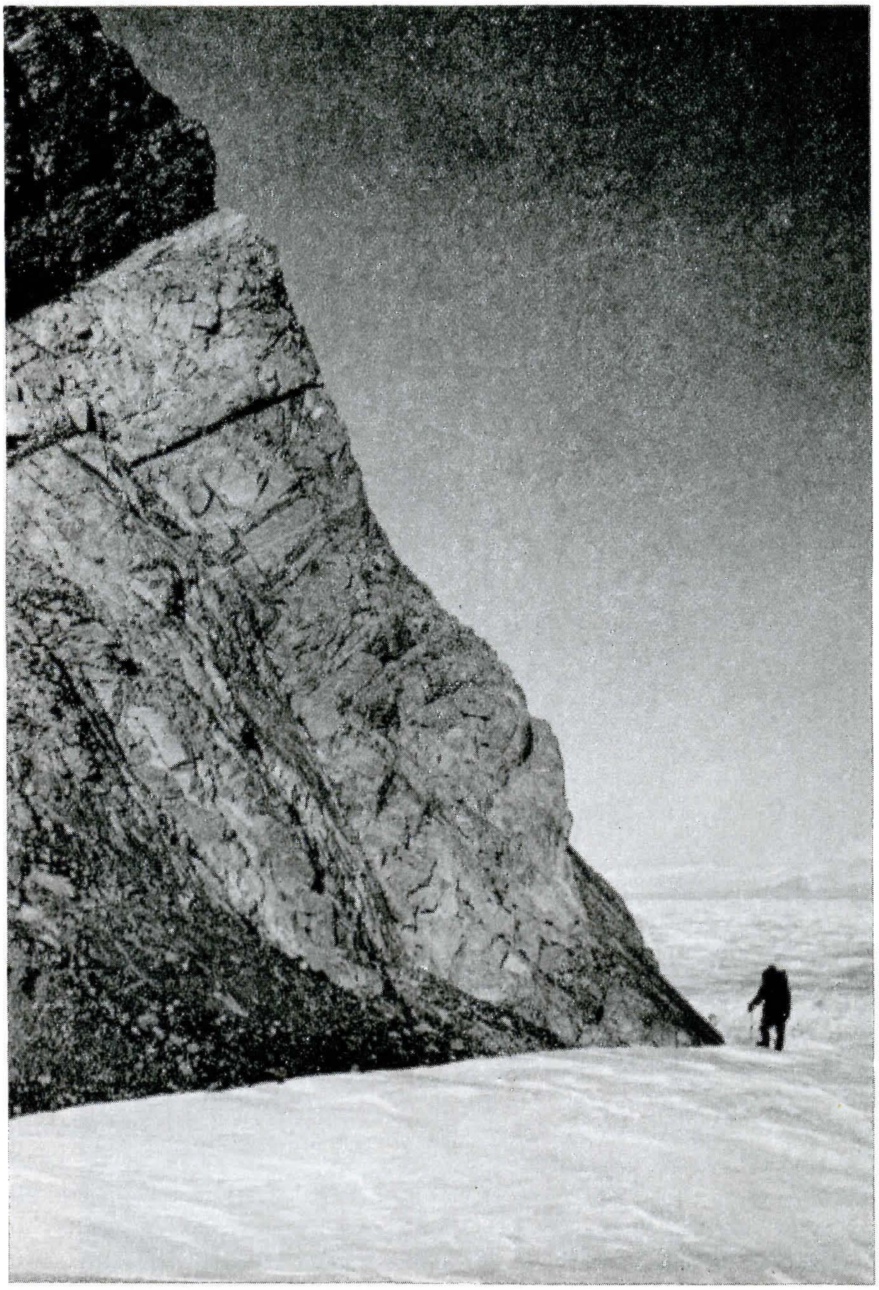

Fig. 4 - "Hope" Granite intruding biotite gneisses of the Nimrod Group, Orr Peak. The contact parallels the gneiss foliation at this locality. Locality 21.

folds occur in several areas. Tight drag folds with subhorizontal axes are fairly common (Fig. 5). In one locality, 3 km south of Orr Peak, the axial plane of a recumbent fold in biotite gneiss and marble exhibits coaxial refolding with intense lateral compression (Fig. 6). The axis of this fold trends north-south. Nearby, another set of tight, upright folds on east-west axes suggests a further phase of crustal compression.

There is little doubt that the regional metamorphism of the Nimrod Group is associated with the main phase of deformation. Only in one of the rocks examined so far (sample 79) is there evidence of porphyroblastic crystal growth after the generation of the foliation. Locally near the margins of the granite stocks contact metamorphism and metasomatism have been superimposed. The age of the deformation and metamorphism is still in doubt. The Ordovician date on the Hope Granite provides a minimum age. Grindley (1967, p. 559) quotes radiometric dates which "indicate metamorphism approximately 1,000 m.y. ago." These are K-Ar dates (I. McDougall, personal communication).

Block faulting, a common phenomenon in the Transantarctic Mountains, may have affected the Miller Range. The basal unconformity of the Beacon rocks is a generally sub-planar surface. Projection of this surface across the Marsh Glacier fails to clear the higher summits of the Miller Range. This has led Grindley to suggest (1967, p. 559) that the Miller Range has been upfaulted by at least 100-200 meters. He also describes post-metamorphic normal faulting within the Nimrod Group. These faults have northerly trends and downthrow to the east. The age of this faulting is unknown (Grindley, McGregor and Walcott, 1964, p. 210).

PETROGRAPHY

Mica Schists

Schistose fabric, fine to medium grain size, essential biotite or muscovite, and quartz characterize these rocks. Seven samples were examined, six of them in thin section. The mica schists show considerable variations in mineralogy, which could be the basis for further subdivision. Rocks containing 50 percent or more of quartz are transitional to metaquartzites. Other essential or auxiliary minerals are plagioclase (andesine), garnet, hornblende, tremolite, diopside, and chloritoid. Magnetite, orthoclase, epidote and sphene are accessory minerals. Parallelism of mica flakes dominates the foliation. Amphiboles, where present, generally have their long axes within the foliation planes. One sample (79) contains an incipient S_2 foliation developed by crenulation of S_1.

Quartz and plagioclase occur as equant xenoblastic grains, commonly with sutured margins. Where these minerals predominate they form a granoblastic framework, within which the mica flakes are distributed. Where mafic minerals are dominant, quartz and plagioclase form

Fig. 5 - Drag fold in somewhat porphyroblastic biotite gneiss. Fold axial plane dips gently westward. Locality 92A.

Fig. 6 - Coaxially refolded recumbent fold in biotite gneisses. Axial planes strike north. Locality 31, Augen Bluffs.

solitary grains within a felted framework of micas and amphiboles. All gradations between these extremes exist. Brown to green idioblastic biotite is present in all but one of the samples examined. Muscovite has a similar habit but is less common. Deformed cleavages in both micas occur in several rocks. Amphiboles are xenoblastic. Porphyroblastic garnet, probably almandine, occurs in two of the samples. In sample 79, a chloritoid-biotite-garnet schist (Figs. 7-10), garnet porphyroblasts form more than 30 percent of the thin section. They range between 0.1 and 2.0 mm across and are concentrated in layers 4 to 5 mm thick, which alternate with relatively garnet-free felsic layers. The garnet crystals contain trains of inclusions parallel to the foliation. Elongate randomly oriented green porphyroblasts of chloritoid form more than 7 percent of this section. In sample 16 small rounded and indented crystals of diopside containing magnetite inclusions form 5 to 10 percent of the rock. The remainder of this rock is composed of biotite, quartz, K-feldspar and plagioclase. A 2-cm glomeroporph of garnet from sample 18, an augen gneiss which is interbanded with biotite schist, was analyzed for refractive index and x-ray powder diffraction spectrum. The results indicate a composition very close to pure almandine.

Banded Gneisses

These rocks are distinguished by prominent segregation banding of felsic and mafic minerals which gives them a typical gneissic fabric. Felsic bands are typically 5 to 10 mm apart. There appears to be a continuous gradation from weakly gneissic rocks (such as sample 17A) with discontinuous streaks of mafic material in a felsic matrix, through strongly gneissic rocks (such as sample 38) with minor porphyroblasts, to augen gneisses where the abundance of coarse augen disrupts the gneissic foliation. Distinction of banded gneisses and augen gneisses is therefore arbitrary. In all cases the gneisses approximate to granitic mineralogy and composition. They are generally coarse grained and gray in color. Principal minerals are quartz, microcline, oligoclase, biotite, hornblende and muscovite. Accessories include apatite, sphene, magnetite, ilmenite, epidote and diopside. Felsic minerals make up 75 percent or more of the rocks.

Microcline is invariably an essential mineral in these rocks. The grains are usually xenoblastic, white to pink in hand specimen and little altered in thin section. Grain size is variable; in porphyroblastic rocks there are commonly two size generations, less than 0.5 mm and more than 2.0 mm. Quantities range up to 40 or 50 percent of rock volume. Quartz may be more or less abundant than microcline. Grains are typically xenoblastic and commonly between 0.1 and 1.0 mm. In some rocks they are elongate parallel to the lineation. Strained extinction is very common.

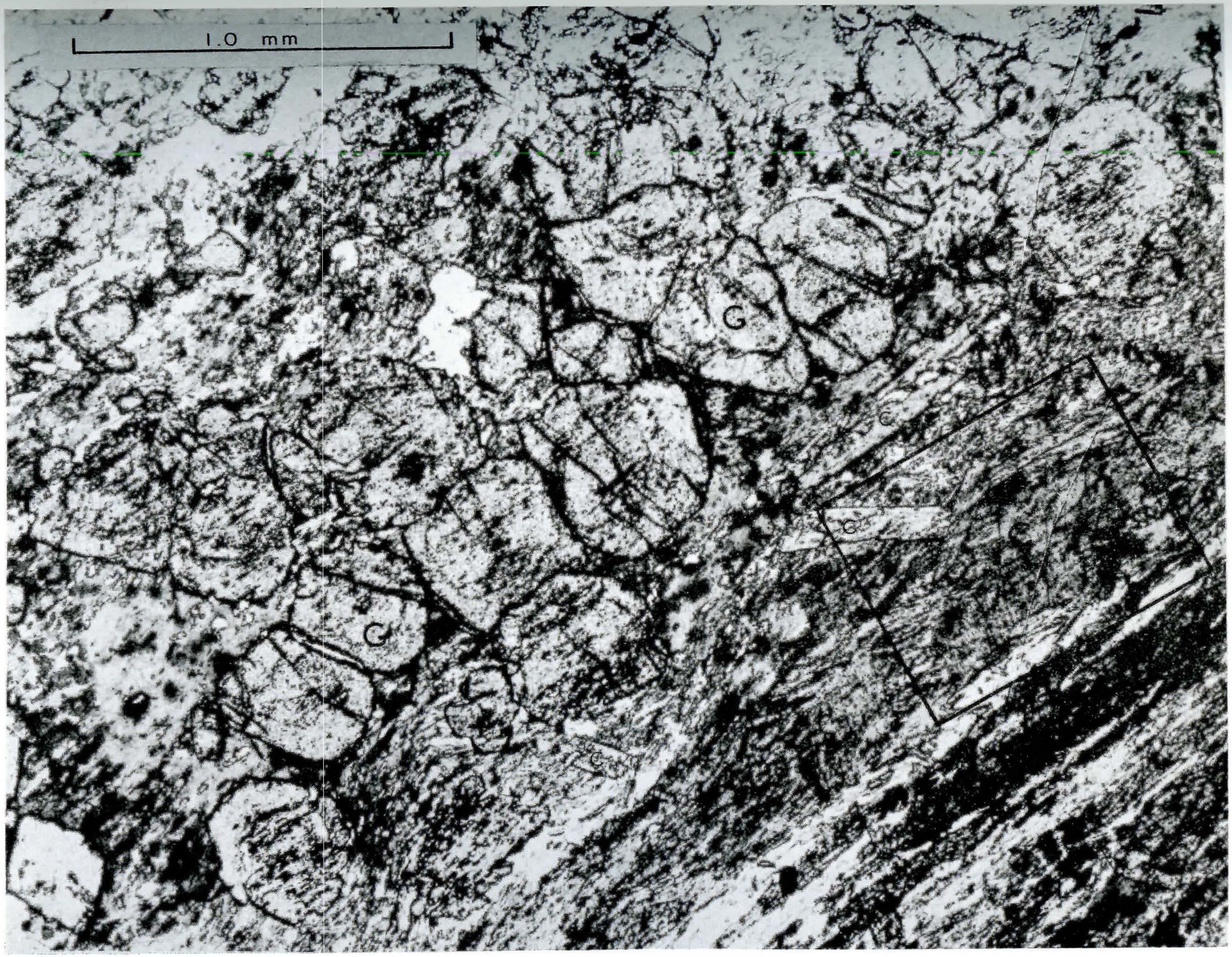

Fig. 7 - Porphyroblastic garnet (G) and chloritoid (C) in mica schist. Area of Figs. 8 and 9 outlined. Sample 79. Plane polarized light.

Fig. 8 - Chloritoid porphyroblasts with long axes oblique to foliation (horizontal). See Fig. 7. Sample 79. Plane polarized light.

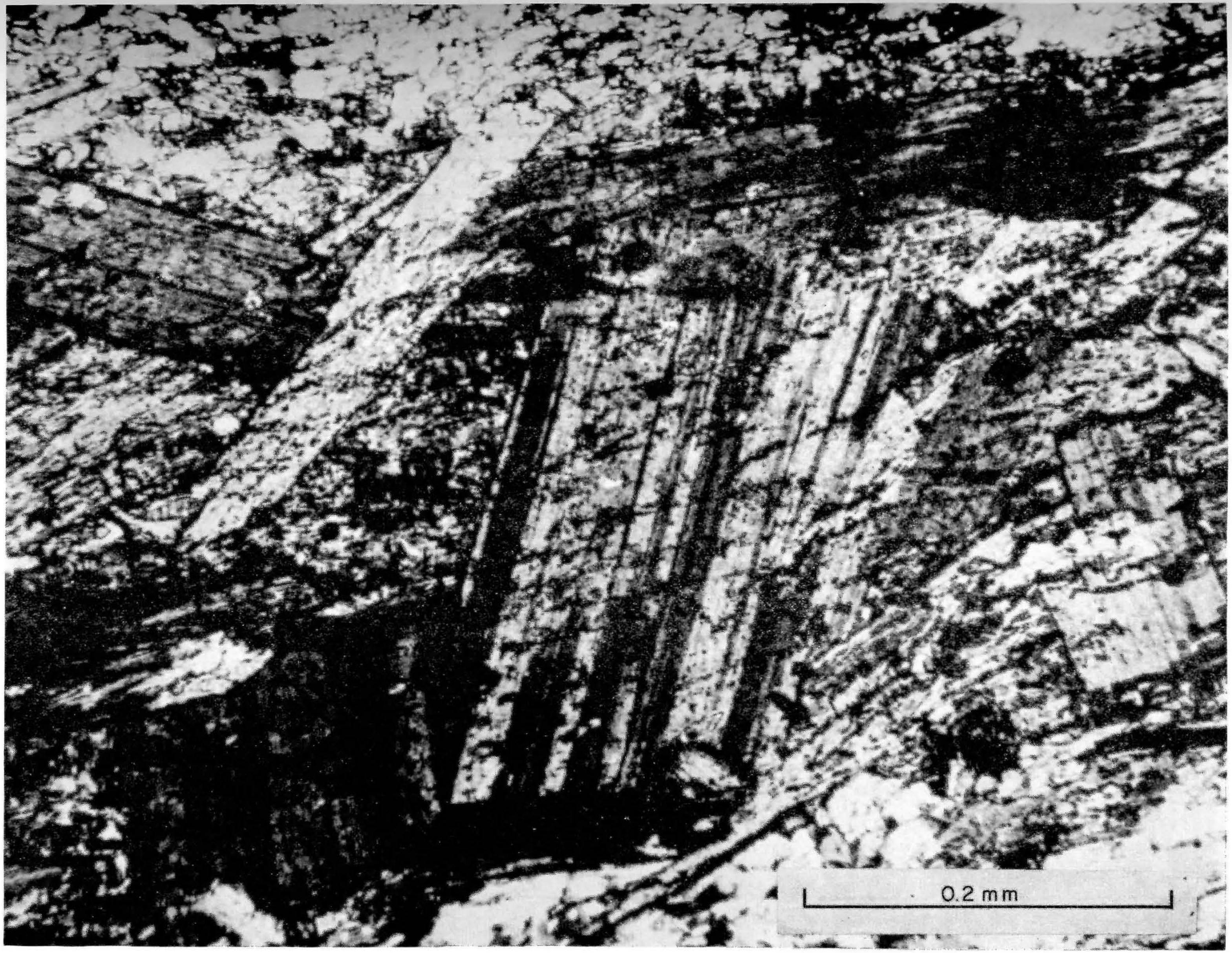

Fig. 9 - Same as Fig. 8. Crossed nicols.

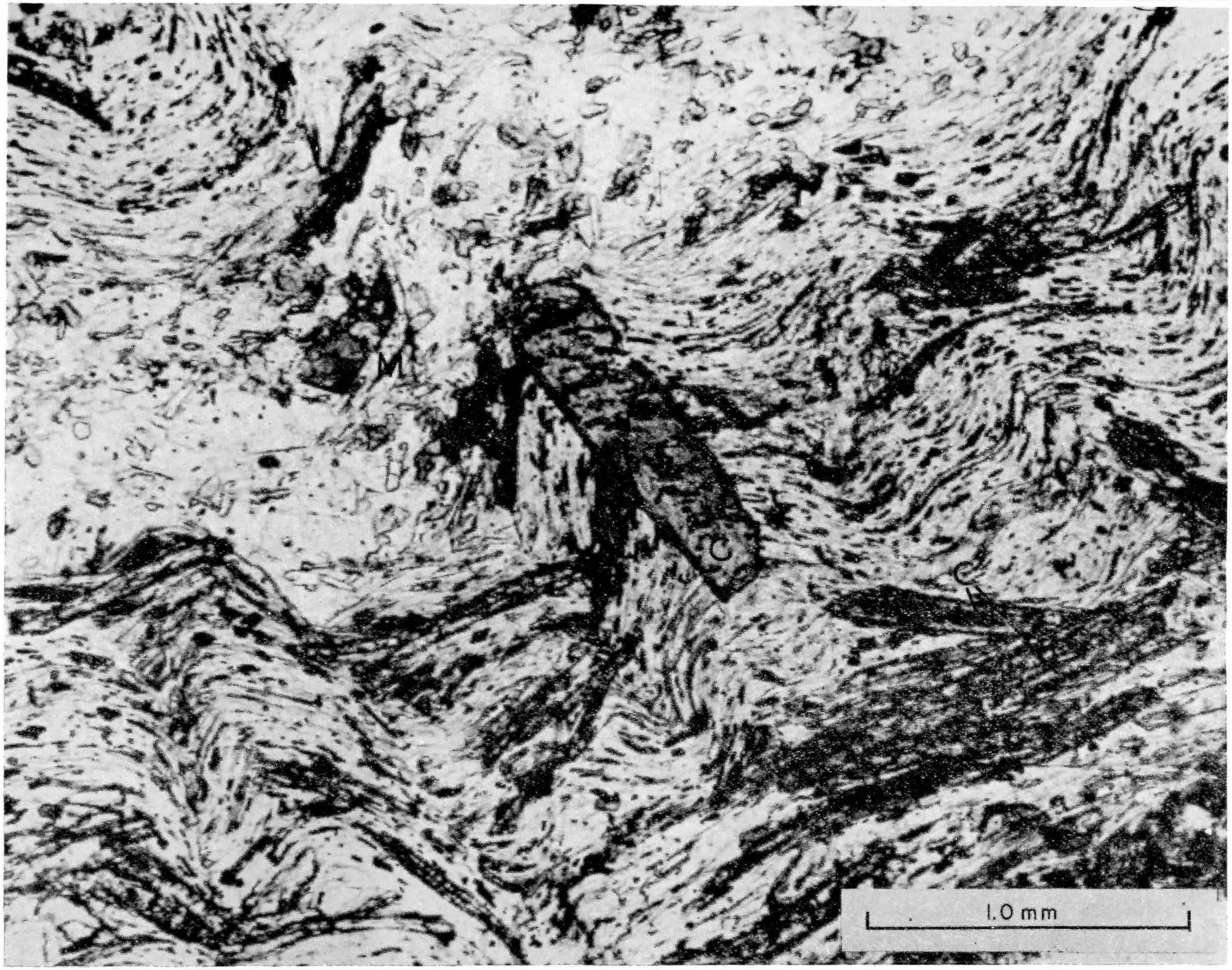

Fig. 10 - Crenulated foliation in mica schist. Chloritoid porphyroblast (C) contains opaque inclusions which are oriented parallel to the earlier foliation. Micas are mostly muscovite (M). Sample 79. Plane polarized light.

Plagioclase is generally less abundant than microcline but is present in all the sections examined. Compositions range from An_2 to An_{20}. In shape and size the plagioclase compares with microcline, although grains more than 2.0 mm are rare. Alteration to sericite and saussurite is noticeable in some rocks but generally not extensive. Strained extinction is again common. Some rocks contain local quartz-plagioclase intergrowths. Dark green pleochroic hornblende occurs in many of the gneisses and may form 15 percent of rock volume. Grains are generally xenoblastic, often with ragged outlines. Porphyroblasts up to 4 or 5 mm are present in some rocks. A common associated mineral is brown biotite. It occurs in similar quantities to hornblende, and the two minerals form aggregates and clusters in the mafic layers. Biotite crystals, however, are generally idioblastic and show less tendency than hornblende to form large porphyroblasts. A common maximum length is 1 or 2 mm, and in finer-grained rocks the flakes average less than 1 mm. Up to 5 percent of muscovite occurs especially in the leucocratic gneisses. Crystal sizes and shapes are generally comparable to those of biotite.

Augen Gneisses

The augen gneisses (Fig. 11) are characterized by large porphyroblasts of feldspar set in a medium-grained matrix of quartz and feldspar with biotite and, in some rocks, hornblende. The porphyroblasts vary from rounded idioblastic crystals to lensoid augen. Parallel orientation of augen and elongate matrix mineral confer a strong lineation on some rocks. Strained extinction in quartz and feldspar, deformed feldspar twin lamellae, and mechanically induced twinning in plagioclase are very common. Several samples have microscopic cataclastic textures at the augen margins, which suggest rolling of the augen during deformation.

The augen gneisses differ little from the banded gneisses in mineralogy and composition. The augen consist of large (1.0 to 40.0 mm long) rounded crystals of microcline (Figs. 12 and 13), less commonly plagioclase (Fig. 14), of composition An_2 to An_{20}, and occasionally quartz-feldspar aggregates. In some rocks the augen are rimmed by fine-grained (about 0.1 mm) aggregates of quartz, plagioclase and microcline (Figs. 13 and 14), which contrast with the average matrix grain size of 0.5 to 1.0 mm. Mafic minerals, principally biotite and hornblende, are segregated into thin fine-grained bands and streaks within the dominantly granoblastic matrix. These bands are generally parallel to foliation, or, where there is a lineation, to the augen margins.

Metaquartzites

These rocks (Figs. 15 and 16) are medium to coarse grained and their grain sizes range up to 4.0 mm. Quartz and feldspar grains form

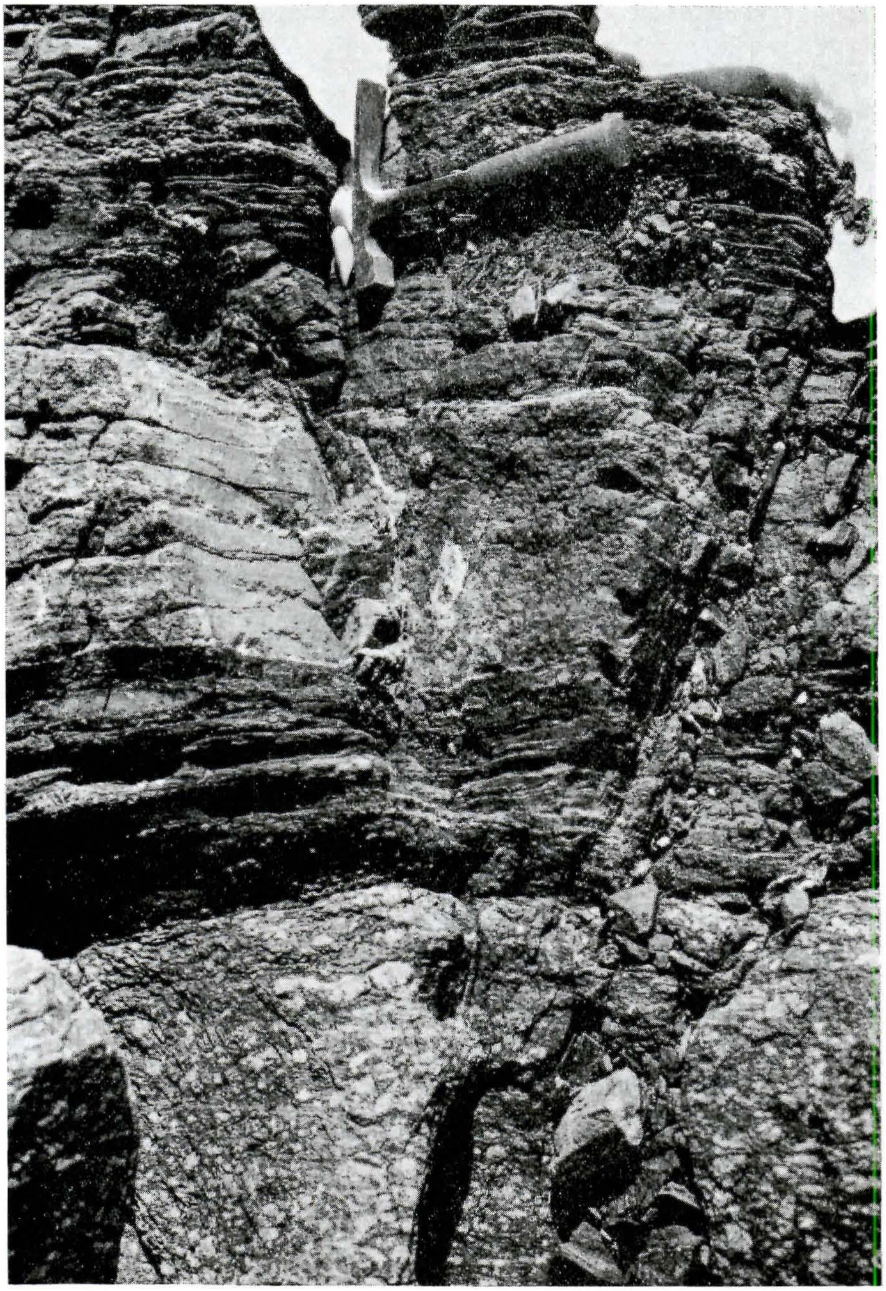

Fig. 11 - Interlayered banded gneiss and augen gneiss.
Locality 31, Augen Bluffs.

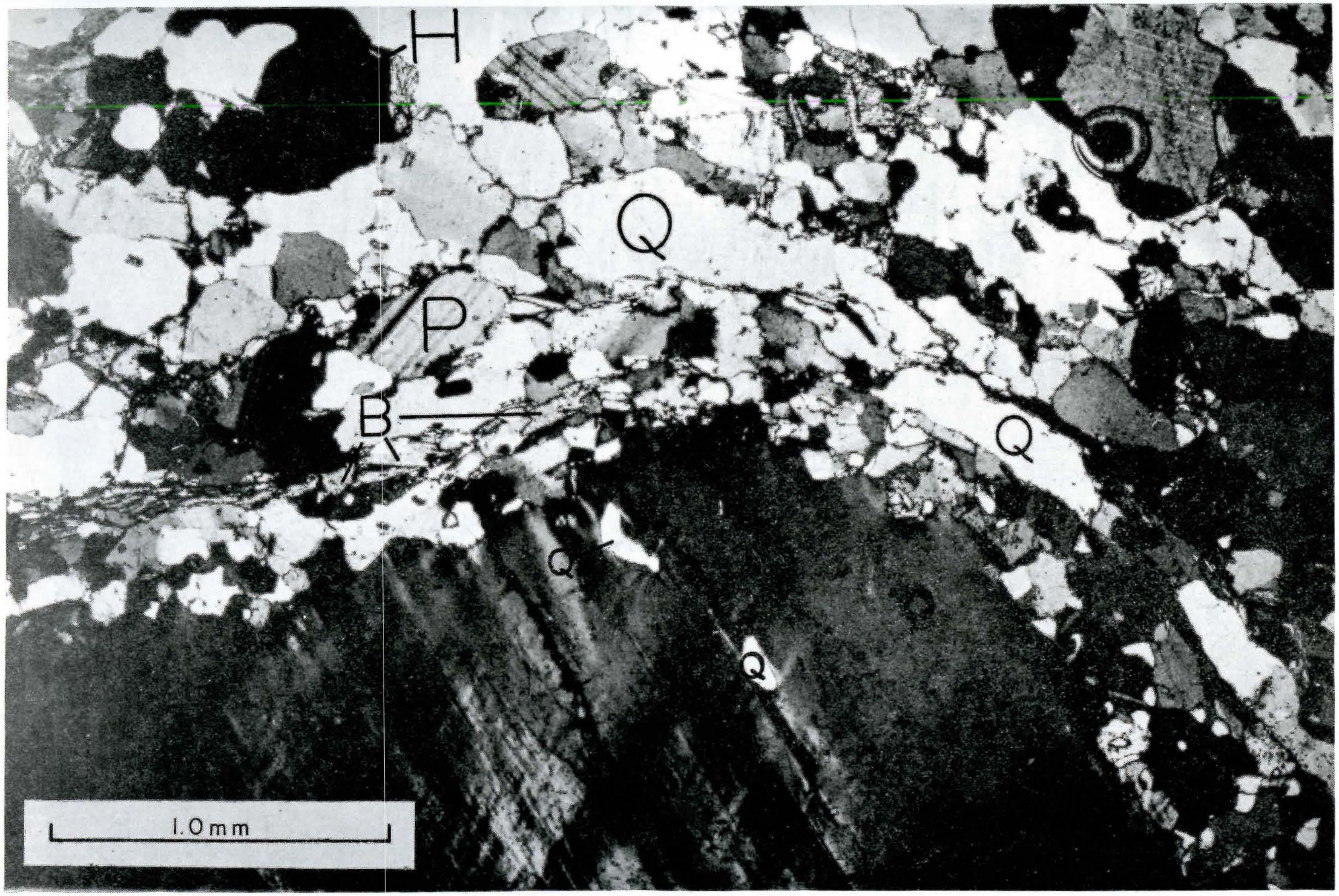

Fig. 12 - Margin of microcline porphyroblast in augen gneiss. The matrix contains quartz (Q), plagioclase (P), microcline, biotite (B) and hornblende (H). Finer grain size at the augen margin suggests granulation. Sample 32. Crossed nicols.

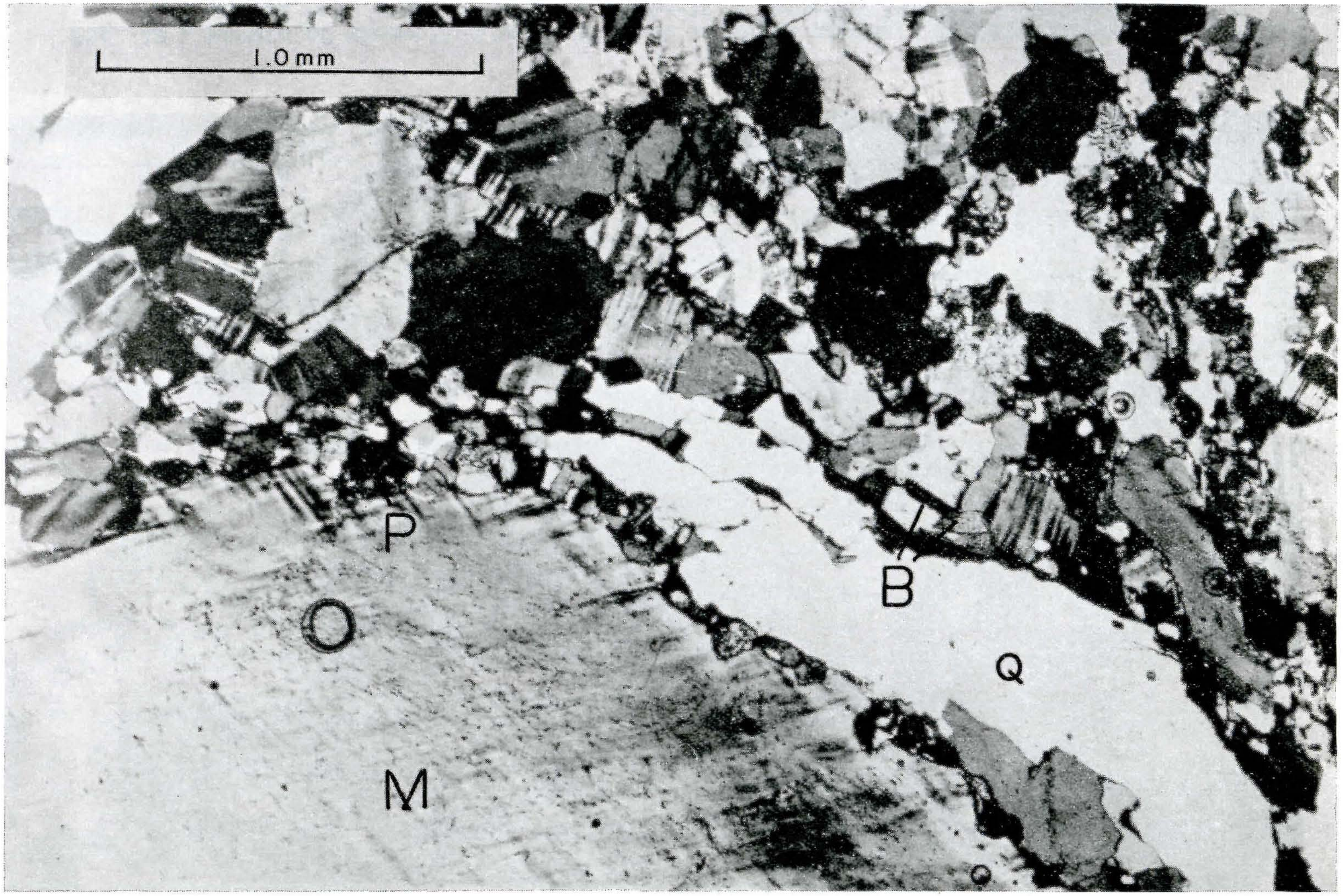

Fig. 13 - Same as Fig. 12. Here microcline (M) is the dominant feldspar in the matrix. The coarse-grained quartz (Q) may have recrystallized in a reduced pressure zone caused by counter-clockwise rotation of the porphyroblast.

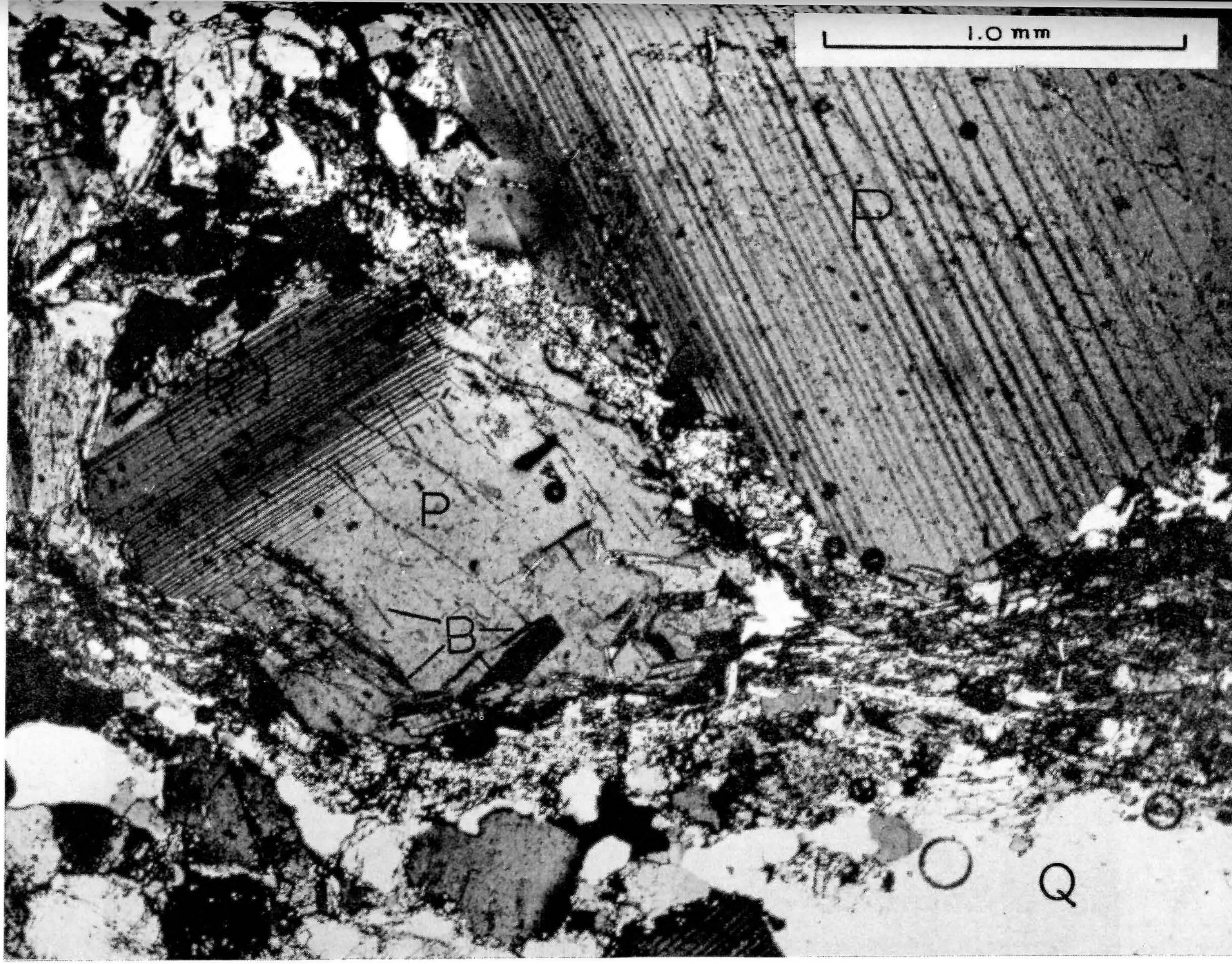

Fig. 14 - Two porphyroblasts of albite-oligoclase (P) in augen gneiss. Biotite flakes (B) in the matrix are aligned parallel to the augen margins. Quartz (Q) and plagioclase are also present in the matrix. Sample 18A. Crossed nicols.

Fig. 15 - Laminated impure metaquartzite and schist (North ridge, Kreiling Mesa); the presence of sharp and gradational contacts between schist and metaquartzite may represent relict graded bedding.

Fig. 16 - Relict cross-stratification in metaquartzites, north ridge, Kreiling Mesa. Coin is 2.5 cm in diameter. Locality 76.

a granoblastic fabric with grain contacts more or less sutured. Platy and elongate minerals are generally aligned, showing a lepidoblastic or nematoblastic sub-fabric.

Quartz, the dominant mineral in these rocks, forms xenoblastic grains up to 4.0 mm across. These vary in shape from equidimensional to elongate parallel to the foliation or lineation. Strained extinction is very common. Petrofabric studies on a thin section of sample 8 indicate strong preferential orientation of quartz c-axes in one direction and a weaker orientation in a girdle at right angles (see Fig. 25). Plagioclase occurs in two of the four thin sections studied. Composition in the more siliceous rocks is oligoclase. In the other, which is transitional to a tremolite schist, the plagioclase is andesine. The grains are commonly equant and xenoblastic with margins which vary from straight to sutured. They are generally comparable in size to quartz, showing little alteration and in many cases have strained extinction. Small idioblastic flakes of fresh brown biotite occur in minor quantities in two of the rocks examined and confer a foliation on them. In rocks from Kreiling Mesa magnetite occurs in significant quantities (up to 13 percent modally). In sample 77 there are two size generations: idioblastic porphyroblasts averaging 0.5 mm across (Fig. 17), and more xenoblastic, somewhat elongate, grains up to 0.1 mm long in the groundmass. Idioblastic flakes of muscovite up to 0.1 mm long also occur in sample 77, giving the rock a weak lepidoblastic fabric. Sillimanite forms about 5 percent by volume of sample 74, which contains about 75 percent quartz. The sillimanite occurs as sheaves of fresh, colorless, idioblastic prisms (Figs. 18 and 19) up to 1 mm in length. Parallelism of these prisms gives the rock a weak nematoblastic fabric, which is not visible in hand specimen. Sillimanite is distributed more or less equally through the rock. The sample was collected about 500 meters from the granite of Martin Dome, so that the presence of sillimanite may be due to thermal metamorphism. Tremolite and diopside, 4 percent and 14 percent, respectively, occur in sample 8, together with andesine and accessory biotite. Bladed idioblastic crystals of tremolite are oriented subparallel giving the rock a lepidoblastic fabric and a prominent lineation in hand specimen. Ragged porphyroblasts of diopside are associated with this tremolite.

Marbles

The marbles (Fig. 20) are composed of calcite with subordinate tremolite, diopside, muscovite, biotite, plagioclase, potash feldspar, sphene and apatite. Six samples were examined, four in thin section. These rocks range in texture from fine (less than 0.5 mm) to coarse grained (more than 3.0 mm). Most have a granoblastic fabric, although a weak nematoblastic fabric is developed in some of the impure marbles. Colors are generally light: white, cream, yellow or gray.

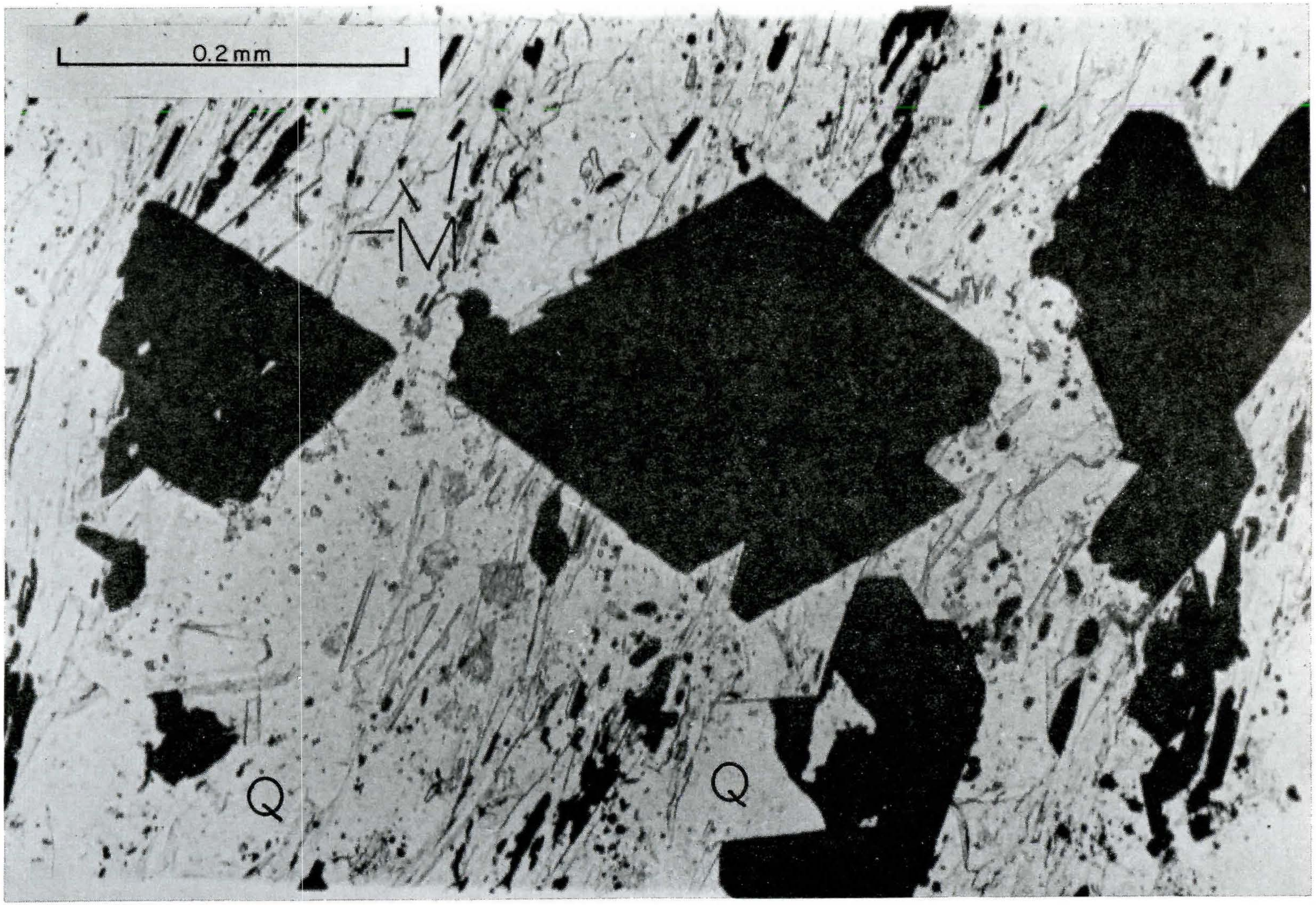

Fig. 17 - Idioblastic porphyroblasts of magnetite (M) in muscovite metaquartzite.
Sample 77. Plane polarized light.

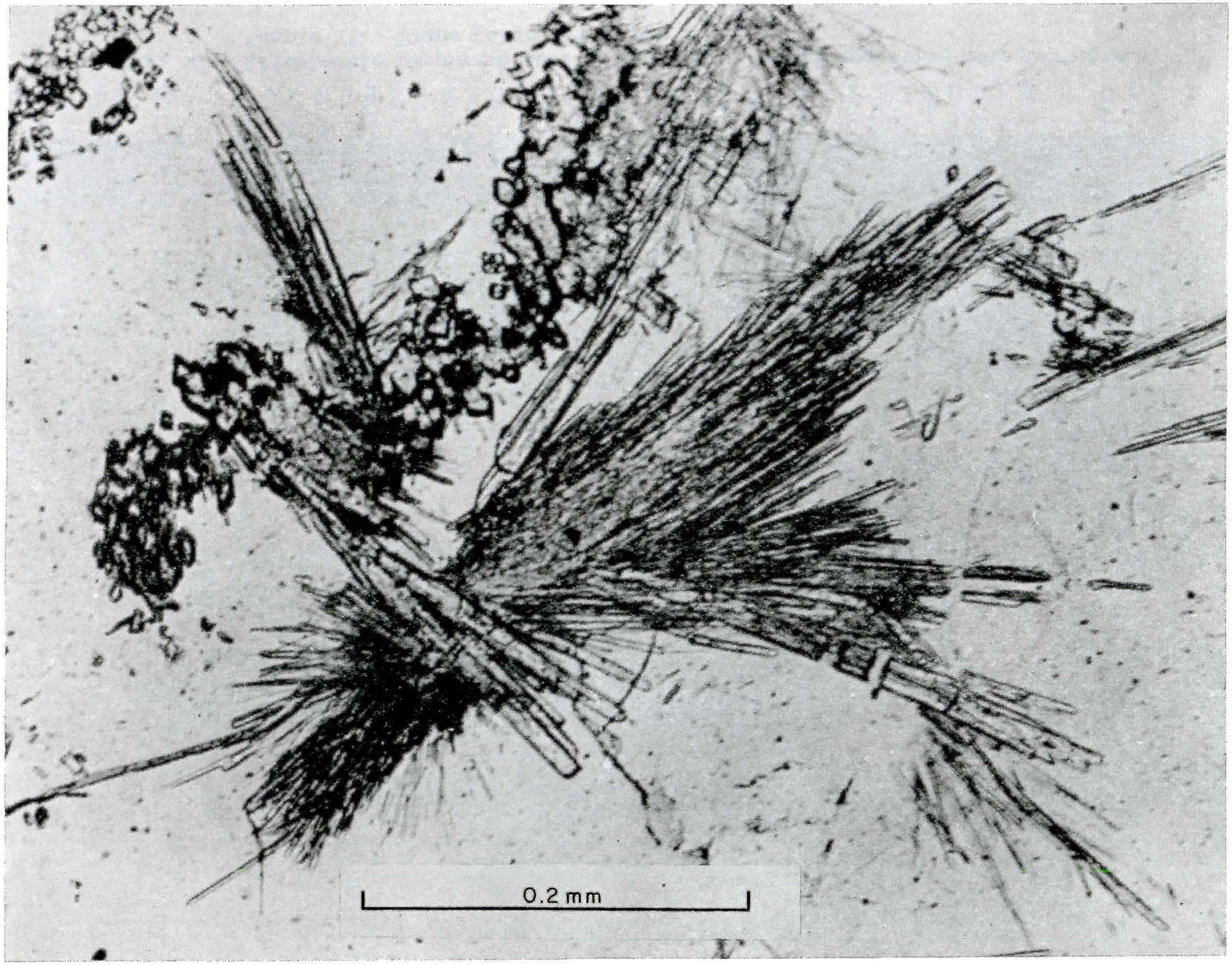

Fig. 18 - Sheaves of sillimanite in metaquartzite. Sample 74. Plane polarized light.

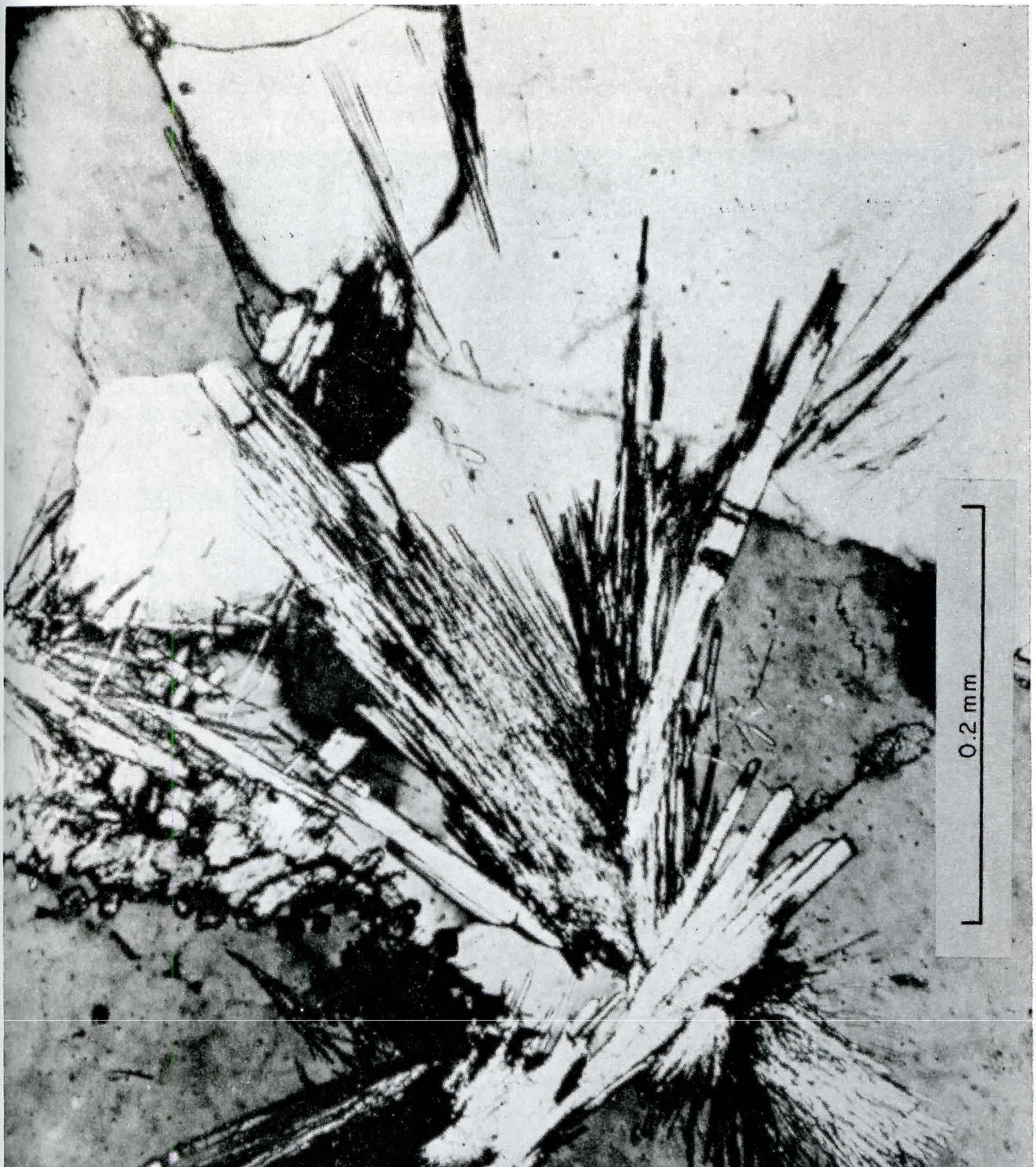

Fig. 19 - Same as Fig. 18. Crossed nicols.

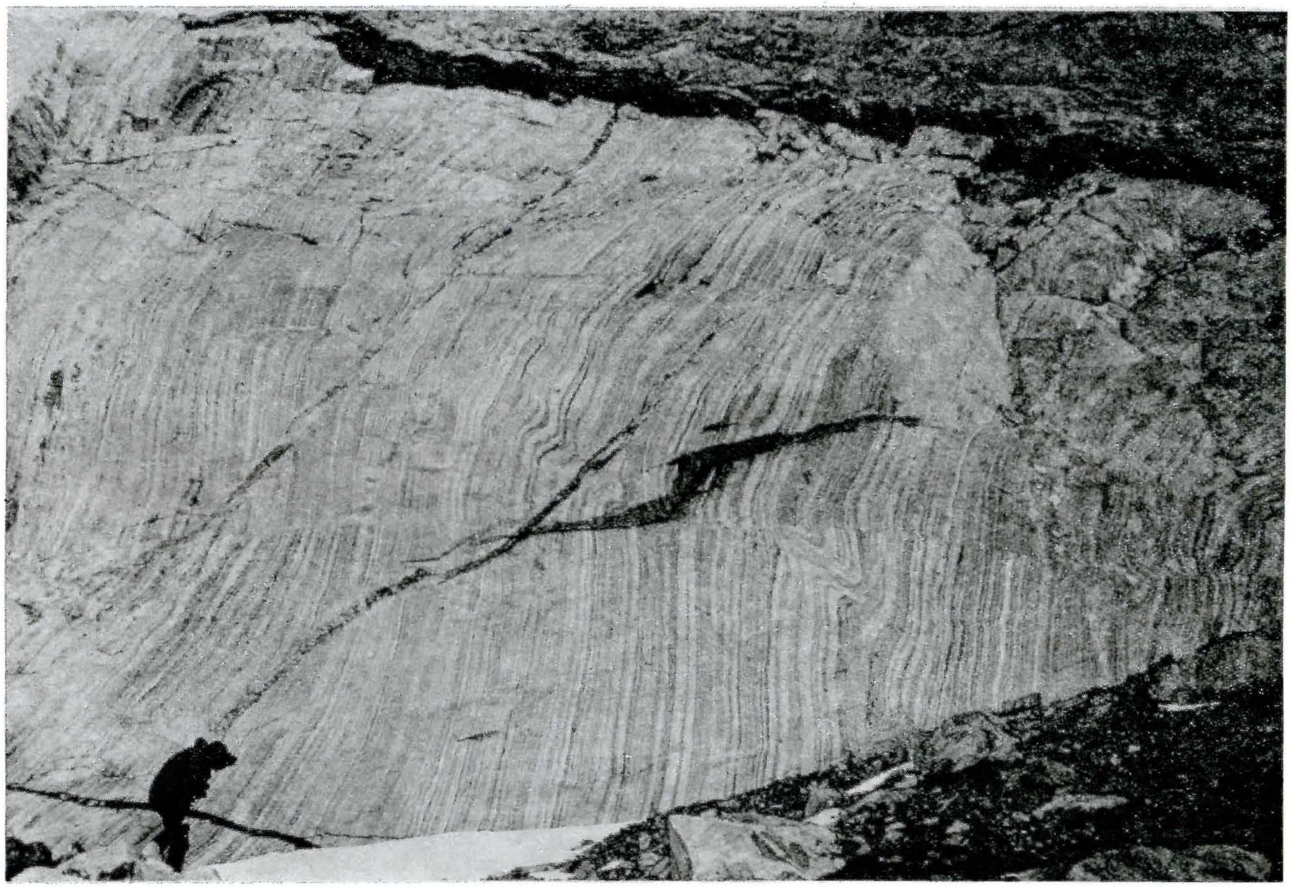

Fig. 20 - Banded marbles intruded by mafic dike. Dike Cirque. Locality 46.

Calcite forms fresh, colorless equant grains which are mostly xenoblastic. Sizes range from less than 0.1 mm to more than 3.0 mm. Fresh tremolite occurs as separate idioblastic crystals, colorless in thin section, and as sheaves and rosettes. The crystal long dimensions tend to show a crude parallelism. Fine- to medium-grained muscovite is present in two of the samples sectioned. Parallelism of the flakes, where in sufficient quantity, gives the rock a foliation. In sample 10 the muscovite cleavages are prominently deformed. Graphite forms up to 5 percent of sample 15. Subparallelism of the flakes gives the rock a weak foliation. Rounded porphyroblasts and smaller grains of orthoclase are also present in sample 15. These have prominent undulose extinction. A third accessory mineral in this rock is diopside, which forms somewhat poikiloblastic porphyroblasts up to 1.0 mm in size.

Amphibolites

The amphibolites (Figs. 21 and 22) characteristically contain essential hornblende and plagioclase. Biotite is very common (up to 25 percent of rock volume). Significant amounts of pyroxene (diopside or augite) occur in three of the nine thin sections examined. Garnet, sphene, magnetite and apatite are accessory minerals. Quartz occurs in several rocks. It is believed that this is mostly metasomatically introduced, although some may be accessory.

The amphibolites are medium grained, well foliated and, in some cases, lineated. Where hornblende is the dominant mineral the fabric is usually nematoblastic; where there is abundant biotite a partly lepidoblastic fabric results. Very little segregation banding occurs in the rocks sampled. Quartzo-feldspathic bands in samples 2 and 11 are interpreted as metasomatic or hydrothermal.

Plagioclase is the only essential felsic mineral in these rocks. In most cases it is a calcic andesine (about An_{45}). Crystals are generally xenoblastic, equant, little altered, and about 0.5 to 1.0 mm across. Extensive untwinned plagioclase occurs in several of the samples as shown by amaranth staining. Strained extinction and mechanical twinning are common but not so prominent as in the augen gneisses. In samples 2 and 11 the plagioclase is albite, both in the quartzo-feldspathic bands and in the main rock. The bands in sample 11 contain antiperthite. Those in sample 2 connect with a patch of biotite pegmatite. Both rocks contain more than 5 percent modal quartz, but neither contains epidote. Two explanations for the anomalous presence of quartz and albite in these rocks are possible. Either they are part of the primary metamorphic mineral assemblages of the rocks or they have been introduced metasomatically. The evidence indicates that the second alternative is the more likely.

Hornblende occurs in modal proportions between 25 and 75 percent. Commonly it forms ragged xenoblastic grains, pale green to dark green,

Fig. 21 - Highly contorted, interbanded marbles and amphibolites.
Fig. 22 is at lower right of picture. Locality 2, Gerard Bluffs.

Fig. 22 - Same as Fig. 21, showing close-up.

and between 0.5 and 2.0 mm across. In several rocks it poikiloblastically encloses small crystals of plagioclase, biotite, quartz, sphene, and magnetite. Green, brown or reddish-brown crystals of biotite are generally similar in size to hornblende but are idioblastic. Several of the rocks contain markedly deformed biotite. Xenoblastic grains of diopside, up to 2.0 mm across and notably full of inclusions, occur in samples 3 and 20. In sample 34 (Fig. 23) small grains of augite less than 0.5 mm across contain very fine exsolution lamellae of hypersthene or pigeonite parallel to (100). This may be a relict igneous texture. Porphyroblastic garnet, probably almandine, is present in four of the samples examined. Shapes may be idioblastic, rounded or indented; sizes range up to 3.0 mm. Trains of inclusions are common in the larger porphyroblasts. In at least one case these indicate rotation of the garnet after growth (Fig. 24).

SUMMARY OF MINERAL PARAGENESES

Table 2 summarizes the mineral occurrences in the six lithologic groups considered in this paper. Mineral assemblages grouped chemically are listed below. The assemblages within each group are arranged in order of abundance. Where relative abundances are not indicated the assemblages are bracketed. Auxiliary minerals are placed in parentheses. Order within each assemblage is arbitrary.

<u>Pelitic</u>

{Quartz-andesine-biotite-garnet
Quartz-(oligoclase/andesine)-hornblende-biotite}

{Quartz-andesine/labradorite-tremolite-biotite
Quartz-muscovite-biotite-chloritoid-garnet
Quartz-orthoclase-plagioclase-diopside-biotite-chloritoid}

<u>Quartzo-feldspathic</u>

{Quartz-microcline-oligoclase-(diopside)-hornblende
-muscovite-biotite-(epidote)
Quartz-andesine-diopside-tremolite-(biotite)
Quartz-orthoclase-plagioclase-biotite}

{Quartz-(biotite)-sillimanite
Quartz-muscovite-magnetite}

<u>Basic</u>

{Andesine-diopside-hornblende-garnet
(Quartz)-andesine-augite-hornblende-biotite
(Quartz)-andesine-diopside-hornblende-biotite}

<u>Calcareous</u>

{(Quartz)-calcite-orthoclase-andesine/labradorite-diopside
-graphite
Calcite-muscovite
Calcite-tremolite}

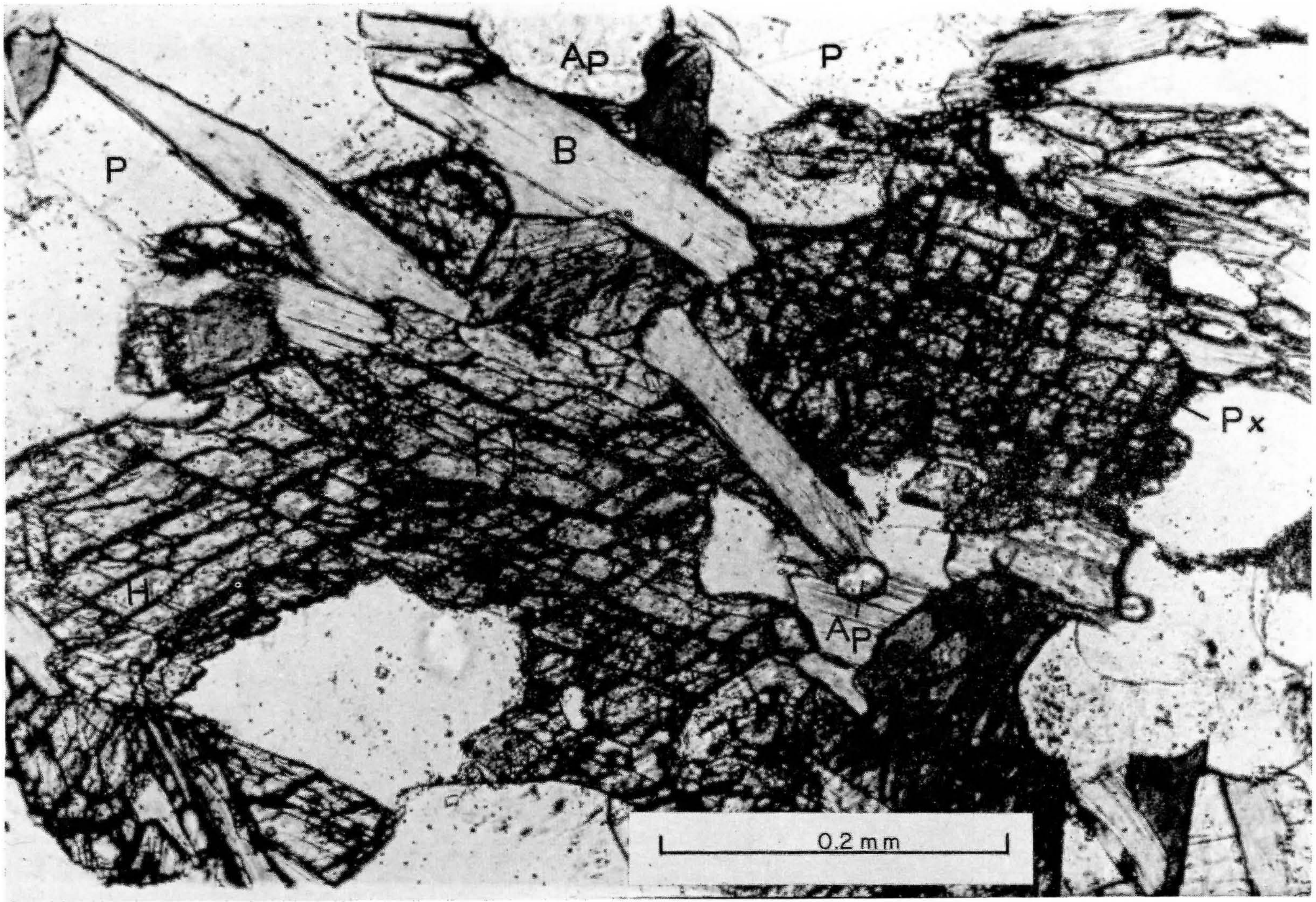

Fig. 23 - Biotite amphibolite showing hornblende (H), biotite (B), augite (Px), plagioclase (P), and apatite (Ap). Sample 34. Plane polarized light.

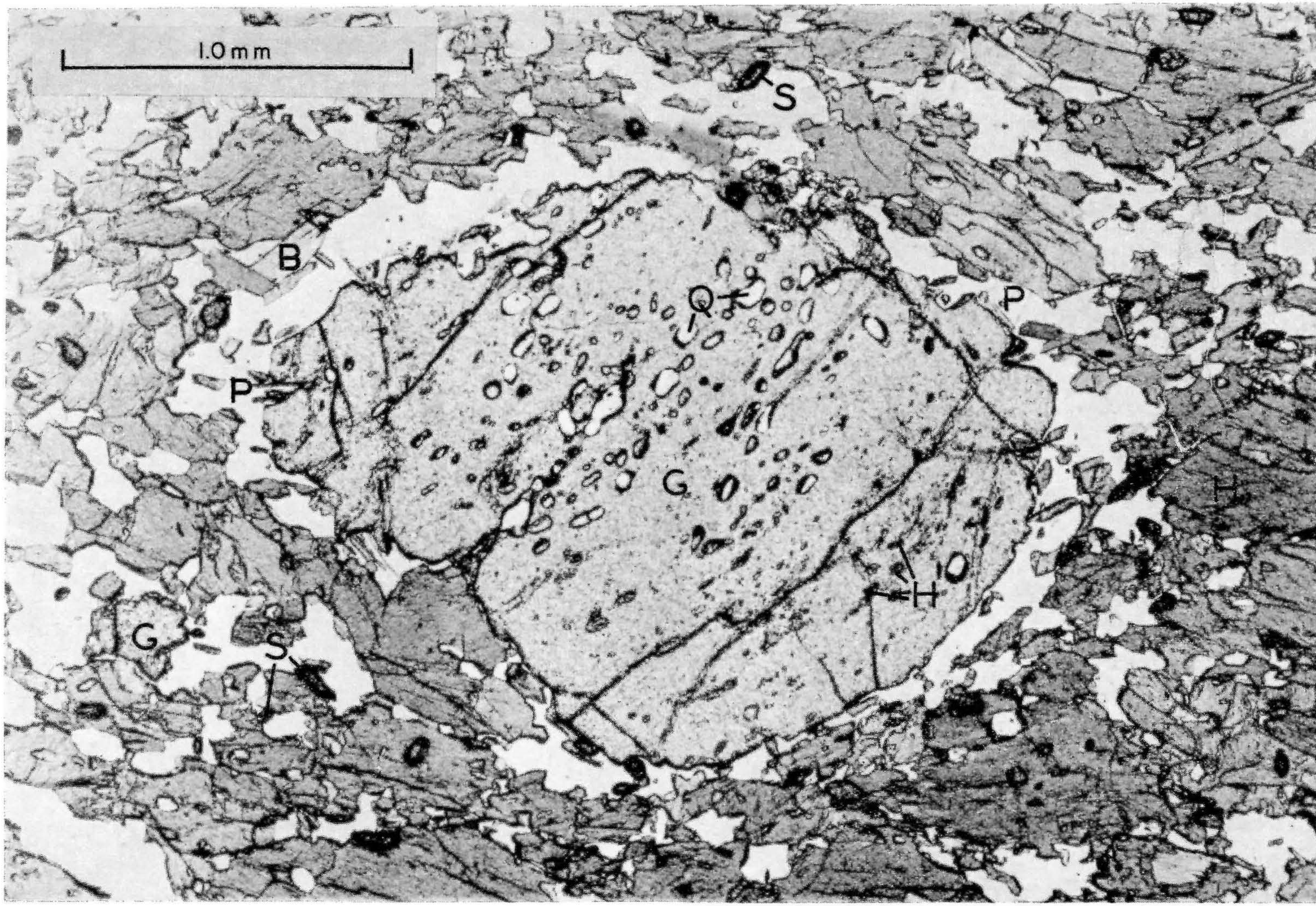

Fig. 24 - Garnet porphyroblasts (G) in biotite amphibolite. The slightly sigmoidal trains of inclusions (quartz and hornblende) are oblique to the foliation. This indicates rotation of the crystal during and after growth. Other minerals are plagioclase (P), quartz (Q), hornblende (H), biotite (B) and sphene (S). Sample 2. Plane polarized light.

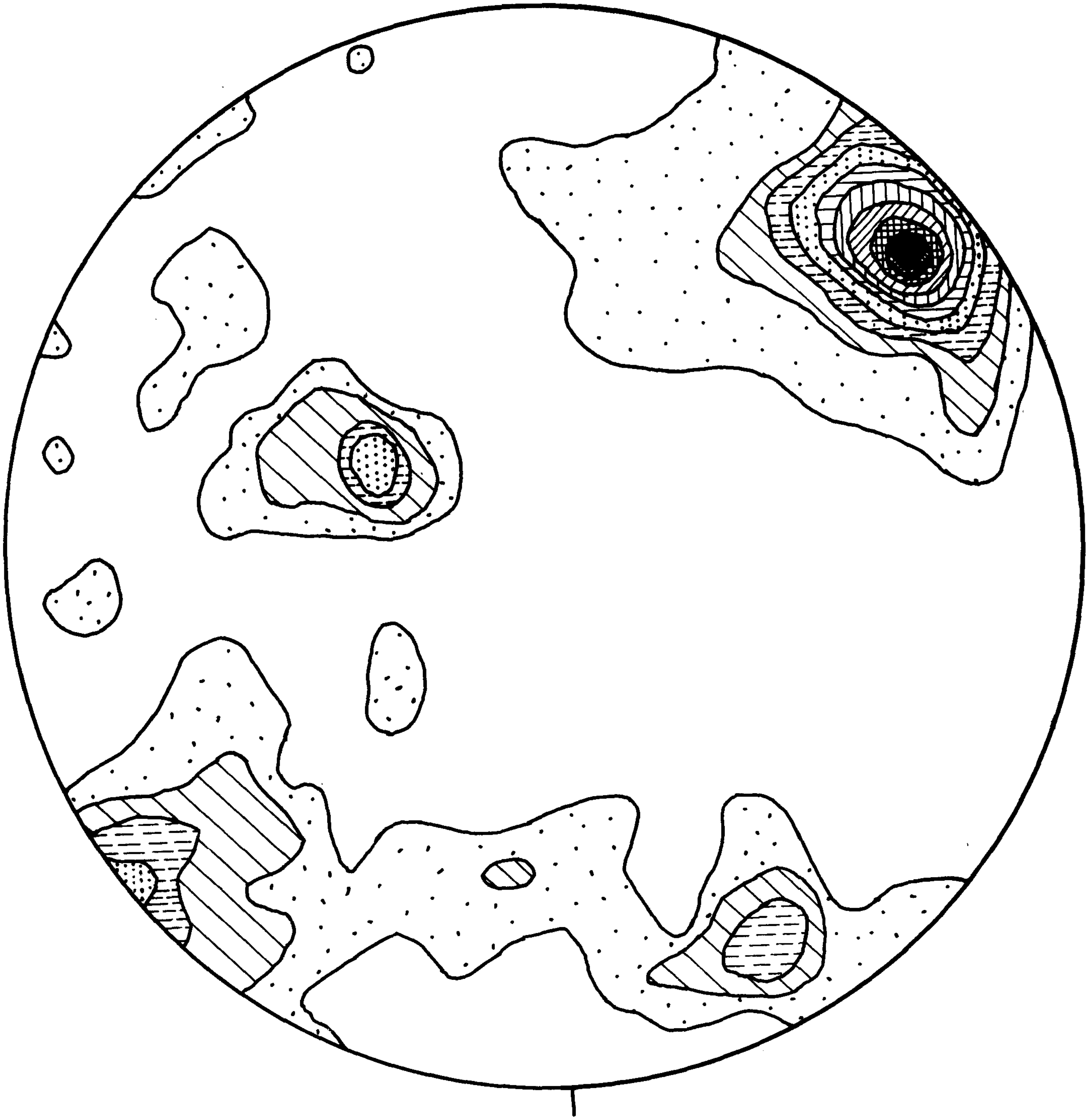

Fig. 25 - Lower hemisphere stereographic projection of 300 quartz c-axes in metaquartzite. Sample 8.

Table 2 - Mineral Parageneses of the Nimrod Group

	Meta-Quartzites	Banded and Augen Gneisses	Mica Schists	Amphibol-ites	Marbles
Quartz	————	————	————		
Orthoclase			— - —		
Microcline		————			
* Albite		* —	* —		
Oligoclase		———			
Andesine (labradorite)			———	————	
Diopside	— - —	— - —	— - —	— - —	— - —
Augite				— - —	
Hornblende		— - —	— - —	————	
Tremolite	— - —		— - —		— - —
Muscovite	— - —	————	— - —		— - —
Biotite	— - —	————	————	————	
Chloritoid			— - —		
Garnet		— - —	— - —	— - —	
Sillimanite	— - —				
Sphene		- - - - -	- - - - -	- - - - - - - - - -	
Epidote		- - - - -	- - - - -		
Apatite		- - - - -			- - - - -
Magnetite	- - - - -		- - - - -	- - - - -	
Calcite					————
Graphite					- - - - -

*Plagioclase composition albite/oligoclase

————	Essential
— - —	Auxiliary
- - - - - - - - - -	Accessory and invariable
- - - - -	Accessory and occasional

Alternative essential minerals

———	predominant
—	subsidiary

All these mineral assemblages belong to the Barrovian facies series (Winkler, 1967). The fact that plagioclase generally contains more than 15 percent anorthite indicates that these rocks belong to the almandine-amphibolite facies (Winkler, 1967, p. 106). Albite or albite/oligoclase occurs in two banded gneisses and one mica schist. However, these rocks contain little or no epidote (less than 0.3 percent modally), so that the presence of albite or sodic oligoclase may be due to lack of calcium, rather than to metamorphic facies. The presence of chloritoid in two pelitic parageneses is not unequivocally diagnostic of the greenschist facies. Winkler states that "chloritoid...appears stable in some mineral associations within the lowermost grade of the amphibolite facies." An alternative explanation is that the chloritoid is retrograde. Sample 79 contains more than 7 percent modal porphyroblastic chloritoid, which has grown after the development of foliation. This rock was collected within 1 km of the granite of Kreiling Mesa. It is therefore possible that the chloritoid may have formed by retrograde metamorphism of the schist imposed by intrusion of the granite.

Sillimanite occurs in only one rock sectioned, sample 74, which is otherwise an almost pure quartzite. According to Winkler (1967, p. 177), sillimanite indicates almandine-amphibolite facies conditions, at temperatures of at least 600°C. In any case this sample was collected within 1 km of the Martin Dome granite, so the possibility of contact metamorphism cannot be excluded. The dominance of andesine and general scarcity of labradorite, coupled with the presence of chloritoid, indicates that the rocks were not metamorphosed beyond the lower almandine-amphibolite facies, and probably belong to the staurolite-almandine subfacies.

CHEMICAL PETROLOGY

No chemical analyses are available at present. This section concerns chemical analyses calculated from modal analyses and is therefore subject to all the limitations which this procedure involves. Tables 3, 4, and 5 summarize analyses calculated for amphibolites, metaquartzites, banded gneisses, and mica schists. At least 1,000 points were counted in each modal analysis. Mineral analyses were obtained from Deer, Howie, and Zussman (1962-63, 1966). Mineral analyses from rocks most closely corresponding to the sample analyzed were chosen. Conversion of volume percent to weight percent was made using mean specific gravities from the same sources. The most firm conclusions on parent rocks can be made

The most firm conclusions on parent rocks can be made in the case of the amphibolites. Five of the seven modal analyses computed were selected. The remaining two (samples 2 and 11) show evidence of later igneous or hydrothermal effects. The chemical analyses calculated for samples 3, 9, 20, 34, and 95 are listed in Table 3. Columns 6 and 7 give Manson's average analysis for 1,996 basaltic rocks and the standard deviation for his samples, respectively (Manson, 1967, in Poldervaart and Hess, p. 236). FeO and Fe_2O_3 percentages are summed in parentheses, since the oxidation state of iron is not significant. The percentages

Table 3 - Amphibolites: Five Chemical Analyses Calculated from Modes, Compared with Analyses of Average Basaltic Rocks (Manson, 1967)

Column	1	2	3	4	5	6	7	8	9
Sample	3	9	20	34	95				
SiO_2	46.94	46.32	47.52	50.39	49.20	49.5	3.23	46.27	52.73
TiO_2	2.00	1.47	0.94	0.86	1.79	1.9	1.03	0.87	2.93
Al_2O_3	14.04	14.89	14.39	16.90	17.96	15.9	2.13	13.77	18.03
Fe_2O_3	1.60	1.16	1.25	1.21	0.87	3.0	1.35	1.65	4.35
	*(14.27)	(13.80)	(12.47)	(11.15)	(10.34)	(11.0)		(7.75)	(14.25)
FeO	12.67	12.64	11.22	9.94	9.47	8.0	1.90	6.10	9.90
MnO	0.34	0.32	0.26	0.18	0.19	0.17	0.10	0.07	0.27
MgO	7.46	7.37	8.49	5.90	5.45	6.6	2.11	4.49	8.71
CaO	11.65	11.07	11.15	8.62	7.86	10.0	1.46	8.54	11.46
Na_2O	1.80	1.80	1.63	2.21	3.46	2.7	0.76	1.94	3.46
K_2O	0.36	0.75	1.62	2.29	1.93	1.0	0.65	0.35	1.65
H_2O^+	1.21	1.34	1.52	1.42	1.52	0.9	0.73	0.17	1.63
H_2O^-	0.09	0.87	0.09	0.10	0.19				
P_2O_5	-	-	-	-	0.19	0.33	0.25	0.08	0.58
Totals	100.16	100.95	100.08	100.02	100.08	100.0			

*Total FeO + Fe_2O_3 in parentheses

Column	
6	Average of 1,996 basaltic analyses
7	Standard deviation of this sample
8	Minimum percentage } Chemical screen for basaltic rocks (Manson, 1967, p. 221)
9	Maximum percentage }

Sample	Description
3	Garnet-diopside-hornblende schist
9	Biotite-hornblende schist
20	Diopside-biotite-hornblende schist
34	Augite-biotite-hornblende schist
95	Biotite-hornblende schist

Table 4 - Metaquartzites and Banded Gneisses: Six Chemical Analyses Calculated from Modes, Compared with Analyses of Average Sedimentary Rocks and Granite (Poldervaart, 1955).

Column	1	2	3	4	5	6	7	8	9	10
Sample	74	8	77	91	38					
SiO_2	81.1	80.3	66.9	73.2	71.3	79.7	65.8	62.2	53.5	70.8
TiO_2	-	-	0.2	0.2	1.2	0.3	0.5	0.7	0.8	0.4
Al_2O_3	18.1	6.7	6.2	14.6	11.8	4.8	14.4	16.5	16.9	14.6
FeO / Fe_2O_3	0.8	1.0	23.0	1.9	3.6	1.4	5.3	6.9	13.0	3.4
MnO	-	-	-	-	-	-	0.1	-	1.3	0.1
MgO	0.3	2.7	-	0.6	2.5	1.2	3.0	2.6	2.0	0.9
CaO	-	6.5	-	1.0	1.7	5.6	3.6	3.3	6.0	2.0
Na_2O	-	1.6	0.1	5.0	3.8	0.5	3.5	1.4	1.4	3.5
K_2O	-	0.2	2.5	3.4	3.3	1.3	2.1	3.5	2.0	4.1
H_2O^+	-	0.3	1.0	0.3	0.6	-	-	-	-	-
H_2O^-	-	-	-	-	-	-	-	-	-	-
CO_2	-	-	-	-	-	5.1	1.6	2.7	2.9	-
Totals	100.3	99.3	99.9	100.2	99.8	99.9	99.9	99.8	99.8	99.8

Sample	Description
74	Sillimanite metaquartzite
8	Tremolite-diopside metaquartzite
77	Magnetite-muscovite metaquartzite
91	Muscovite-biotite gneiss
38	Hornblende-biotite gneiss

Column	Average Sedimentary Rocks and Granite (Poldervaart, 1955, pp. 134-5)
6	Average sandstone (Clarke, 1924)
7	Average graywacke (Pettijohn, 1949)
8	Average shale (Clarke, 1924)
9	Average red clay (Sujowski, 1952)
10	Average granite (Daly, 1933)

Table 5 - Mica Schists: Three Chemical Analyses Calculated from Modes, Compared with Average Analyses of Shales and Red Clays (Poldervaart, 1955, pp. 134-5).

Column	1	2	3	4	5
Sample	7	16	79		
SiO_2	59.0	49.2	42.0	62.2	53.5
TiO_2	0.7	1.2	0.9	0.7	0.8
Al_2O_3	17.6	14.8	20.5	16.5	16.9
FeO / Fe_2O_3	7.6	11.5	22.1	6.9	13.0
MnO	0.1	0.1	0.7	-	1.3
MgO	3.7	7.6	6.6	2.6	2.0
CaO	4.0	4.0	0.7	3.3	6.0
Na_2O	2.3	0.9	0.1	1.4	1.4
K_2O	3.4	7.7	3.7	3.5	2.0
H_2O^+ / H_2O^-	1.6	2.5	1.9	-	-
P_2O_5	0.1	0.5	0.1	-	-
Totals	100.1	100.0	99.3	97.1	96.9

Column	Description
1	Garnet-hornblende-biotite schist
2	Diopside-biotite schist
3	Muscovite-chloritoid-garnet-biotite schist
4	Average shale (Clarke, 1924), water free
5	Average red clay (Sujowski, 1952), water free

for SiO_2, Al_2O_3, and MgO in all five samples fall within the standard deviation from the mean of Manson's sample. Total FeO + Fe_2O_3 in sample 3, CaO in sample 3 and K_2O in samples 34 and 95 are somewhat high (0.02, 0.19, 0.64, and 0.28 percent high, respectively). TiO_2 in sample 34, CaO in sample 95, and Na_2O in samples 3, 9, and 20 are somewhat low (0.01, 0.68, 0.14, 0.14, and 0.31 percent low, respectively). Little importance can be attached to the percentages of the minor oxides TiO_2, MnO and P_2O_5. Columns 8 and 9 in Table 3 give minimum and maximum percentages in Manson's chemical screen for basaltic rocks (Manson, 1967, p. 221). All five samples fall through the screen. It can therefore be concluded that, within the limits set by the method of calculation of the analyses, and assuming that no metasomatic changes have affected the parent rocks, the parent rocks of samples 3, 9, 20, 34, and 95, and probably of a substantial proportion of all the amphibolites in the Nimrod Group, were principally basaltic.

Table 4 lists chemical analyses calculated from modes of three metaquartzites and two banded gneisses (columns 1-5). In columns 7-10 are listed chemical analyses of average sedimentary rocks and granite quoted by Poldervaart (1955, p. 135). Comparisons of these analyses gives less conclusive information on parenthood than is the case with the amphibolites. The three metaquartzites are presumably derived from quartz-rich sediments. Sample 74, which is anomalously rich in Al_2O, contains about 25 percent modal sillimanite and 75 percent quartz (see Table 6). The parent rock was probably a pure quartzite containing a certain percentage of clay. Sample 77 contains about 13 percent by weight of magnetite, and 24 percent of muscovite. The high iron and low alumina content may indicate derivation of this rock from a ferruginous quartz-arenite containing some clay. The banded gneisses are probably also of sedimentary origin, in view of their association with marbles and other metasedimentary rocks, and their generally concordant marginal contacts. Chemically their compositions appear to fall between sandstone and graywacke. The compositions are also quite close to granite.

In Table 5 chemical analyses calculated for three mica schists are compared with average analyses of shales and red clays quoted by Poldervaart (1955, p. 135). The mica schists contain a considerably higher proportion of the chemically more variable mafic minerals, principally biotite, than the quartzites and gneisses. Hence less accuracy can be expected in a chemical analysis calculated from a mode. Compared with the composition of Clarke's (1924) average shale the three samples are depleted in silica and enriched in iron oxides and magnesia. The silica contents show wide variability. Sample 79 in particular appears to be extremely poor in silica. This is reflected in the mineralogy, more than 90 percent mafic by weight, and is probably real and not an error introduced in calculation. The iron enrichment may be partly real, although the error potential in calculating iron content in these rocks is high. In particular sample 79 contains about 40 percent by weight of garnet, tentatively assumed, without x-ray data, to be almandine.

Table 6 - Modal Analyses

	Amphibolites					Metaquartzites			Banded Gneisses		Mica Schists		
Column	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample	3	9	20	34	95	74	8	77	91	38	7	16	79
Quartz	1.8			6.2		74.6	57.6	56.0	29.5	32.4	23.4	10.8	11.8
Orthoclase											1.9	14.2	
Microcline									18.8	17.6			
Albite									45.3	29.2		5.2	
Oligoclase					45.8*								
Andesine	22.9	26.0	23.1	37.4			23.5				39.7		
Labradorite													
Diopside	2.6		12.6				13.8					11.5	
Augite				8.2									
Hornblende	68.5	69.8	47.5	25.8	34.4					6.3	1.4		
Tremolite							4.1						
Muscovite								23.9	1.5				1.6
Biotite		3.1	15.3	22.5	17.6	0.2	0.9		4.8	12.6	32.4	55.5	47.8
Chloritoid													7.4
Garnet	1.2										1.1		31.4
Sillimanite						24.9							
Sphene	2.5	1.1			2.0					1.2		1.4	
Epidote										0.1		0.3	
Apatite					0.4					0.4	0.2	1.0	
Magnetite	0.6					0.3		12.9	0.2				
Totals	100.1	100.0	100.1	100.1	100.2	100.0	99.9	100.0	100.1	99.8	100.1	99.9	100.0

*Plagioclase composition oligoclase-andesine

The same error potential exists in calculating magnesia in sample 79. Sample 16, on the other hand, contains 11.5 percent by weight of diopside, so the 7.6 percent figure for magnesia content is probably close to reality. The high potash figure for sample 16 also calls for comment. This is reflected in high contents of biotite (56 percent by weight) and orthoclase (14.2 percent by weight) and is therefore probably real.

As a whole these mica schists show considerable chemical variability, principally in silica and iron. Their chemistry is not inconsistent with derivation from argillaceous sediments enriched in some cases with iron, magnesium and potassium. These elements might have been derived from volcanic sources, although no supporting evidence is available. In view of the potential errors in calculating the chemical analyses and the small number of rocks considered these conclusions are only tentative.

CONCLUSIONS

The rocks examined comprise six lithologic groups: mica schists, metaquartzites, banded gneisses, augen gneisses, marbles and amphibolites. These lithologies can be placed in four chemical subdivisions: pelitic (mica schists), quartzo-feldspathic (metaquartzites, banded gneisses and augen gneisses), calcareous (marbles), and basic (amphibolites). From the petrographic evidence it is reasonably certain that the parent rocks of the amphibolites were principally basaltic. There is also little doubt that the marbles are derived from carbonate sediments of varying purity. The parent rocks of the pelitic and quartzo-feldspathic groups were probably principally sedimentary. Volcanic components may be responsible for the anomalous enrichment in iron and magnesium of some of the mica schists and metaquartzites, notably those from Kreiling Mesa. The mica schists were derived principally from pelitic sediments, and the metaquartzites from quartzitic sediments containing varying quantities of argillaceous or tuffaceous material. The banded gneisses and augen gneisses have chemical compositions between those of average sandstone and average graywacke, and those two types were probably their principal parent lithologies.

The rocks of the Nimrod Group have undergone intense structural deformation. They have been regionally metamorphosed at least to the staurolite-almandine subfacies of the Barrovian almandine-amphibolite facies (Winkler, 1967). There is little doubt that this regional metamorphism is associated with the main phase of structural deformation. Little evidence of retrograde metamorphism exists except in the close vicinity of the granite stocks which intrude the Nimrod Group.

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GEOLOGIC MAP: MILLER RANGE